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Exploring Digital Competitiveness through Bayesian Belief Networks

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Abstract

This study assesses national digital competitiveness by analyzing interdependencies among key factors influencing overall performance. Unlike conventional ranking models that assume equal weighting of pillars, this study uses Bayesian belief network (BBN) models to capture complex, non-linear relationships, offering a more precise identification of critical determinants. The methodology involves constructing BBN models using data from the IMD Digital Competitiveness Ranking 2023 for 64 countries. Three states were assigned to variables—low, medium, and high performance—and the tree augmented naive Bayes (TAN) algorithm was applied to model interdependencies. Thefindings highlight future readiness and knowledge as the most influential pillars, with high-performing countries demonstrating strengths in these areas. Additionally, critical sub-pillars such as adaptive attitudes and regulatory frameworks play pivotal roles. Unlike traditional approaches, this study identifies ripple effects within sub-pillars, demonstrating how targeted improvements in key areas can amplify digital transformation. The results emphasize the importance of a holistic strategy that considers these interconnections rather than isolated improvements. By providing a data-driven prioritization of key factors, this study offers policymakers a novel framework for resource allocation and strategic interventions. It contributes to the literature by challenging traditional schemes, advocating for a more comprehensive understanding of digital competitiveness, and offering guidance for targeted interventions tailored to each country's unique context.

Keywords: Digital competitiveness; Bayesian belief network; future readiness; knowledge; policymaking.

JEL Classification: C44

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1. INTRODUCTION

In the modern era, digital competitiveness has emerged as a fundamental driver of national prosperity and resilience (Chatzistamoulou, 2023). With the rapid advancement of technology and the pervasive influence of digitalization across all sectors, countries that effectively leverage digital tools and strategies are better positioned to achieve sustainable economic growth and societal advancement (Surana et al., 2020). Digital competitiveness encompasses various elements, including robust digital infrastructure, skilled workforce, supportive regulatory frameworks, and vibrant innovation ecosystems (Li et al., 2020). These factors collectively determine a country's ability to navigate the complexities of the digital age and capitalize on emerging opportunities. Consequently, recognizing and prioritizing digital competitiveness has become essential for governments worldwide, as they aim to enhance their global standing, stimulate innovation, and foster inclusive growth for their citizens (Dabbous et al., 2023).

The IMD World Digital Competitiveness Ranking (WDCR) is a comprehensive assessment that evaluates countries' digital competitiveness, measuring their capacity to adopt and leverage digital technologies for societal and economic transformation (Popkova & Sergi, 2023; WDC, 2023). This framework is structured into three pillars, each of which has three sub-pillars. The first pillar, knowledge, focuses on the foundational expertise necessary for technological innovation. Within this pillar, the sub-pillars include talent, training and education, and scientific concentration. Talent refers to the availability of skilled individuals who drive technological advancements. Training and education assess the quality of educational programs, fostering technological proficiency. Scientific concentration reflects investment in research and development, which is vital for innovation.

The second pillar, technology, pertains to the overall environment supporting digital technology development (Buchaev et al., 2023). Sub-pillars under technology include the regulatory framework, capital, and technological framework. The regulatory framework evaluates laws and regulations governing technology adoption and innovation. Capital assesses the availability of financial resources for technological endeavors. The technological framework examines infrastructure and standards facilitating technological development.

The third pillar, future readiness, evaluates a country's readiness to capitalize on digital transformation (WDC, 2023). Its sub-pillars include adaptive attitudes, business agility, and IT integration. Adaptive attitudes gauge openness to change and innovation. Business agility assesses companies' ability to respond to technological shifts. IT integration examines the incorporation of technology into various societal and business aspects.

The knowledge pillar of digital competitiveness holds immense significance for countries in today's interconnected world (Švarc et al., 2021). It serves as the foundation upon which countries build their capacity to innovate, adapt, and thrive in the digital age. At its core, the knowledge pillar encompasses the development and dissemination of digital skills, education systems that promote digital literacy, and the cultivation of a vibrant research and development ecosystem (Sharma et al., 2016). A well-educated and digitally literate workforce not only drives innovation and productivity but also enhances a nation's ability to harness the potential of emerging technologies effectively (Mancha & Shankaranarayanan, 2021). Moreover, investments in research and development foster a culture of innovation, leading to the creation of cutting-edge solutions and industries that propel economic growth (Sarpong et al., 2023).

The technology pillar stands as a crucial component of digital competitiveness for countries, underpinning their ability to effectively utilize and deploy digital infrastructure, tools, and platforms (Paul et al., 2020). In today's rapidly evolving technological landscape, countries that invest in robust digital infrastructure and embrace emerging technologies are better positioned to drive economic growth, enhance productivity, and foster innovation (Vu & Hartley, 2018). The technology pillar encompasses a wide array of elements, including the development of advanced telecommunications networks, the adoption of cloud computing, artificial intelligence (AI), and Internet of things (IoT) technologies, as well as the promotion of digital entrepreneurship and innovation ecosystems (Clarysse et al., 2022). By prioritizing the technology pillar, countries can create an enabling environment for businesses to thrive, attract investment, and spur the development of new industries (Fan & Watanabe, 2006). Moreover, leveraging technology effectively enables governments to improve service delivery, enhance public sector efficiency, and promote digital inclusion, thus contributing to overall societal progress and well-being (Bertot et al., 2016).

The third pillar of future readiness is a critical dimension of digital competitiveness for nations, as it encompasses the ability to adapt, innovate, and anticipate future challenges and opportunities in the rapidly evolving digital landscape (Ciarli et al., 2021). In an era marked by unprecedented technological advancements and disruptions, countries that prioritize future readiness are better equipped to navigate uncertainties and capitalize on emerging trends (Soto-Acosta, 2024). This pillar involves fostering a culture of agility and resilience, investing in continuous learning and upskilling programs, and developing adaptive regulatory frameworks that encourage innovation while safeguarding against potential risks (WDC, 2023). Additionally, nurturing a dynamic and collaborative ecosystem that fosters partnerships between government, industry, academia, and civil society is vital for fostering innovation and staying ahead of the curve (Camboim et al., 2019). By embracing future readiness, countries can proactively address emerging challenges such as cybersecurity threats, digital divide, and ethical considerations related to emerging technologies, while seizing opportunities to drive sustainable growth, prosperity, and societal well-being in the digital age (Ahangama, 2023).

Existing studies on digital competitiveness do not adequately explore the relative importance of various drivers while considering their interdependencies. Moreover, they often overlook the synergistic effects that may exist across different drivers, thus failing to provide a comprehensive understanding of their combined impact. To address this gap, the primary objective of this study is to explore the complex dynamics of digital competitiveness by examining the interdependencies among key pillars and sub-pillars using Bayesian belief network (BBN) models. This study aims to identify and prioritize the critical drivers of digital competitiveness and highlight the differential impact of these factors across countries.

The implications of this study provide policymakers and stakeholders with valuable insights into the key factors influencing digital competitiveness. With this understanding, decision-makers can formulate targeted strategies and policies to enhance the digital ecosystem, promote innovation, and drive sustainable economic growth. The subsequent sections of the paper are organized as follows: section 2 presents an overview of the relevant literature, section 3 outlines the research methodology, section 4 discusses the results, section 5 presents the discussion and implications, and section 6 offers conclusions and directions for future research.

2. LITERATURE REVIEW

Digital competitiveness has emerged as a pivotal concept in contemporary literature, reflecting the increasingly digitalized nature of economies worldwide (Hashim et al., 2024; Siddiqui et al., 2021). As businesses, industries, and countries navigate the complexities of the digital age, understanding and fostering digital competitiveness has become imperative (Asif et al., 2024; Qazi, 2025). Scholars underscore its significance in enhancing productivity, stimulating innovation, and fostering economic growth (Bota-Avram, 2024; Dabbous et al., 2023). Moreover, digital competitiveness enables organizations to adapt to rapidly evolving technological landscapes, thereby ensuring sustainability and resilience in the face of digital disruption (Khurana et al., 2022). Furthermore, in an interconnected global economy, digital competitiveness plays a crucial role in determining a nation's position in the global market, influencing its ability to attract investments, create jobs, and participate in international trade (Luo, 2021). Hence, as digitalization continues to redefine traditional notions of competitiveness, comprehensive strategies aimed at bolstering digital capabilities are essential for organizations and nations alike to thrive in the digital era (Liu et al., 2024).

The knowledge pillar of digital competitiveness has been extensively examined in the literature, highlighting its pivotal role in shaping organizational and national performance in the digital economy (Cetindamar Kozanoglu & Abedin, 2021). Access to knowledge resources, particularly digital knowledge, has been emphasized as critical for organizations to effectively leverage digital technologies (Volberda et al., 2021). This emphasis extends to the significance of knowledge creation, acquisition, and dissemination in fostering innovation and competitiveness in the digital age (Forés & Camisón, 2016). Moreover, investments in digital skills have been shown to positively impact organizational performance, enhancing productivity and innovation capabilities (Benitez et al., 2022). At the national level, the importance of investments in education, research, and digital infrastructure has been underscored to create an environment conducive to digital knowledge creation and diffusion (Osei, 2024).

The technology pillar of digital competitiveness has gained significant attention in academic research, highlighting the transformative role of digital technologies in shaping organizational and national competitiveness (Nambisan et al., 2019). Scholars emphasize the importance of technological infrastructure, such as broadband connectivity and digital platforms, in enabling organizations to harness the full potential of digitalization (Saarikko et al., 2020; Sestino et al., 2020). Additionally, studies have explored the impact of emerging technologies, including AI, blockchain, and the IoT, on organizational processes and strategies (Khan et al., 2023; Singh et al., 2020). These technologies are seen as catalysts for innovation, efficiency improvements, and new business models, thus enhancing competitiveness in digital markets (Qazi & Al-Mhdawi, 2024a). Furthermore, research has examined the role of technology adoption and digital maturity in driving organizational performance (Forliano et al., 2023). At the national level, investments in digital infrastructure and the adoption of advanced technologies have been identified as key drivers of digital competitiveness (Gruber, 2019; Skare & Riberio Soriano, 2021).

The future readiness pillar of digital competitiveness has become a central theme in contemporary literature, with a particular emphasis on adaptive attitudes, business agility, and IT integration (Silva et al., 2022). Scholars underscore the necessity for organizations to cultivate adaptive mindsets and flexible approaches to navigate the dynamic digital landscape effectively (Soto-Acosta, 2024; Volberda et al., 2021). Business agility, characterized by the ability to swiftly respond to market changes and customer needs, is identified as a key determinant of future readiness (Motwani & Katatria, 2024). Studies highlight the crucial role of IT integration in enabling organizations to streamline operations, enhance collaboration, and innovate rapidly (Holmström & Carroll, 2024; Ravichandran, 2018). Moreover, a proactive stance towards digital transformation initiatives is essential for building future-ready organizations (Gillani et al., 2024). At the national level, policies promoting IT infrastructure development and fostering a culture of innovation are instrumental in enhancing future readiness and sustaining digital competitiveness (Chatzistamoulou, 2023).

Measurement of digital competitiveness has been extensively explored, particularly at the national level, aiming to provide insights into the determinants and outcomes of digital readiness (Basile et al., 2024; Silva et al., 2022). For instance, comprehensive frameworks proposed by researchers encompass indicators such as digital infrastructure, skills, innovation capacity, and regulatory environment to gauge national digital competitiveness (Dhliwayo & Chebo, 2024; Sarangi & Pradhan, 2020; Stankovic et al., 2021; Yunis et al., 2012). These frameworks offer a holistic view of a country's digital readiness, aiding policymakers in identifying areas for improvement and formulating effective strategies. Moreover, cross-national studies provide comparative analyses of digital competitiveness across countries, offering valuable insights into global trends and best practices (Billon et al., 2009; Rubino et al., 2020; Zerfass et al., 2020). Such studies play a crucial role in guiding policy decisions and investments aimed at enhancing national digital competitiveness in an increasingly interconnected world.

Existing studies on digital competitiveness often treat its drivers as independent factors, overlooking the non-linear interdependencies among them. This oversimplified approach fails to capture the complex relationships that exist in the digital ecosystem, leading to an incomplete understanding of the phenomenon. Consequently, valuable insights into the synergistic effects and trade-offs between different drivers are lost, hindering the development of comprehensive strategies for enhancing digital competitiveness. To address this gap, this study adopts a probabilistic network-based modeling approach. By leveraging probabilistic graphical models, this approach enables us to represent and analyze the interactions among various drivers of digital competitiveness in a more realistic manner. It allows for the incorporation of uncertainty into the modeling framework, thereby offering a better understanding of how different factors influence digital competitiveness.

3. RESEARCH METHODOLOGY

This study uses a methodology that integrates the IMD WDCR 2023 data (WDC, 2023) with BBN modeling to analyze digital competitiveness (see the appendix for the data). The WDCR, conducted by the IMD World Competitiveness Center, assesses and ranks countries based on their adoption and utilization of digital technologies (Bota-Avram, 2024). For the 2023 ranking, data from 64 countries are considered, focusing on three primary pillars contributing to digital competitiveness: knowledge, technology, and future readiness. These pillars are further subdivided into nine sub-pillars, encompassing 54 criteria, although the number of criteria varies across sub-pillars. For instance, the sub-pillar of training and education has more criteria than IT integration. Despite these differences, each sub-pillar holds equal weight in the overall consolidation of results, with each contributing approximately 11.1%.

Criteria within the WDCR can be classified as hard data, quantifying digital competitiveness through measurable means (e.g., internet bandwidth speed), or soft data, which assess competitiveness based on perception (e.g., agility of companies). Hard criteria account for two-thirds of the overall ranking, while survey data accounts for the remaining one-third.

Among the 54 criteria, 19 are novel indicators exclusive to the WDCR, while the remainder are shared with the IMD World Competitiveness Ranking. Two criteria serve as background information only and do not contribute to the overall competitiveness ranking (i.e., population and GDP). The culmination of results from the nine sub-pillars leads to the total consolidation, determining the overall ranking within the WDCR framework.

The BBN modeling approach is chosen for its ability to capture complex relationships and uncertainties among variables (Qazi, 2024; Shabankhah et al., 2024). This method is particularly suitable for this study as it can handle the interdependencies among various factors affecting digital competitiveness. BBNs are probabilistic graphical models that represent relationships among variables using a directed acyclic graph (DAG) (Hossain et al., 2022). Nodes in a BBN represent variables, while directed edges denote dependencies between variables. Each node is associated with a conditional probability distribution that quantifies the likelihood of different states of the variable given the states of its parent nodes. BBNs provide a structured framework for reasoning under uncertainty, integrating both domain knowledge and data-driven information (Sakib et al., 2021). This approach is particularly useful for modeling complex systems with interdependent and uncertain variables (Peng et al., 2022). BBNs facilitate efficient probabilistic inference, enabling analysts to make predictions or decisions based on available evidence and prior knowledge (Akhavan et al., 2021). Additionally, BBNs support sensitivity analysis and can highlight critical variables that significantly influence the outcomes of interest (Hosseini & Ivanov, 2020).

The methodology involves several key steps, starting with data collection and classification, followed by the construction and validation of BBN models. Table 1 presents a summary of the key steps taken in the methodology for this study.

Tab. 1 – Steps taken in the methodology. Source: own research

Step	Description
1. Data collection	The study uses the 2023 IMD WDCR data, which evaluates the digital competitiveness of 64 countries.
2. Selection of variables	Three main pillars of digital competitiveness (knowledge, technology, and future readiness) and their nine sub-pillars are selected.
3. Discretization	Each variable is discretized into three uniform-width states, with s1 and s3 representing high and low performance, respectively.
4. Model construction	The tree augmented naive Bayes (TAN) algorithm is applied to construct two BBN models: one linking the three pillars to digital competitiveness, and another linking the nine sub-pillars.
5. Parameter learning	GeNIe software is used for parameter learning to establish the strength of association between interconnected variables.
6. Model validation	*K*-fold cross-validation is performed to test the accuracy of the BBN models, yielding an accuracy of 93% for the two extreme performance states.
7. Sensitivity and mutual value of information analyses	Sensitivity analysis is conducted to identify critical competitiveness drivers, while mutual value of information analysis evaluates the informativeness of each driver.

Input variables for the BBN models are derived from the country rankings for the three pillars and nine sub-pillars of digital competitiveness. Similarly, the target variable is derived from the country rankings for digital competitiveness. Each variable is discretized into three uniform-width states to facilitate modeling (Simsekler & Qazi, 2022), with s1 and s3 representing high and low performance, respectively.

To build the BBN models, the tree augmented naive Bayes (TAN) algorithm is used, which enhances the traditional naive Bayes classifier by incorporating dependencies among predictor variables (Qazi et al., 2024). While naive Bayes assumes conditional independence among predictors given the target variable, this assumption often fails in real-world scenarios where interdependencies exist. TAN addresses this by introducing a tree structure that allows each predictor variable to have at most one additional dependency beyond its connection to the target variable. This structure captures meaningful relationships while preserving the efficiency of the naive Bayes framework (Vizanko et al., 2024).

Two BBN models are developed using TAN: one linking the three pillars (knowledge, technology, and future readiness) to digital competitiveness, and the second model linking the nine sub-pillars to digital competitiveness. This enables a comprehensive analysis of the factors influencing digital competitiveness at both the macro and micro levels.

Validation of the BBN models is conducted using the *k*-fold cross-validation technique (Marcot & Hanea, 2021). This approach ensures the robustness and generalizability of the models by testing their performance on different subsets of the data. The accuracy of both models is assessed as 93%, with a focus on predicting the extreme performance states of digital competitiveness.

The sensitivity analysis is performed to evaluate the robustness of the models to changes in input variables, while the mutual value of information assessment provides insights into the importance of variables and their mutual information sharing within the models (Qazi & Al-Mhdawi, 2024b). These analyses enhance the reliability and interpretability of the BBN models, enabling a comprehensive understanding of the factors driving digital competitiveness (Xiao et al., 2023).

4. RESULTS

4.1 BBN model for prioritizing pillars of digital competitiveness

Figure 1 illustrates the first BBN model, depicting the interconnectedness of three core pillars with digital competitiveness. In a TAN model, arrows typically flow from the outcome variable to predicted variables; however, this depiction contradicts the interpretation of causal relationships (Al Nuairi et al., 2024). For example, a link from digital competitiveness to future readiness suggests that future readiness influences digital competitiveness, the targeted variable. Unlike treating the three pillars as autonomous factors in the conventional ranking scheme (WDC, 2023), the BBN model reveals interdependencies among them. For instance, technology directly influences both future readiness and knowledge. Each variable follows a uniform distribution due to the use of a uniform-width discretization scheme in model development, implying an even distribution of countries across the three performance states of each variable in this study.

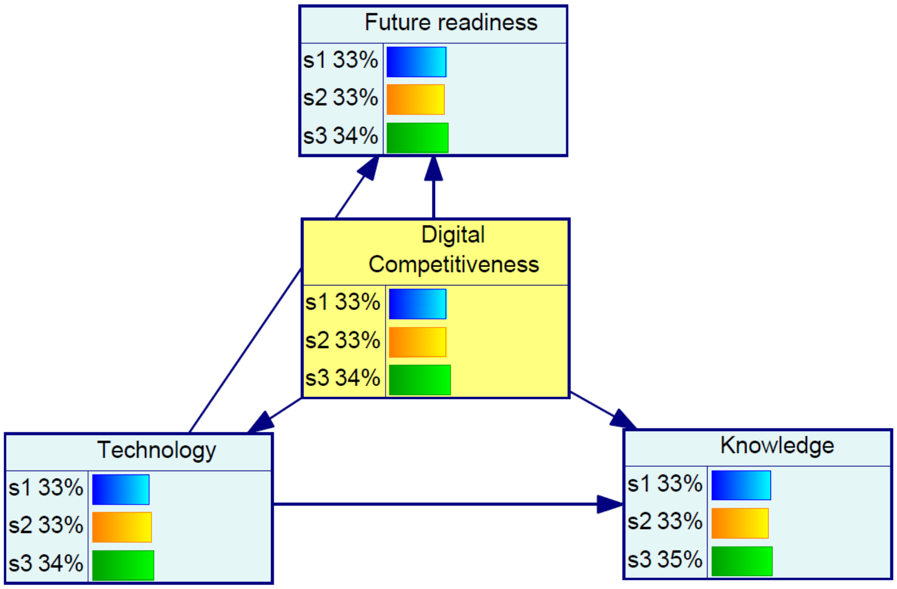
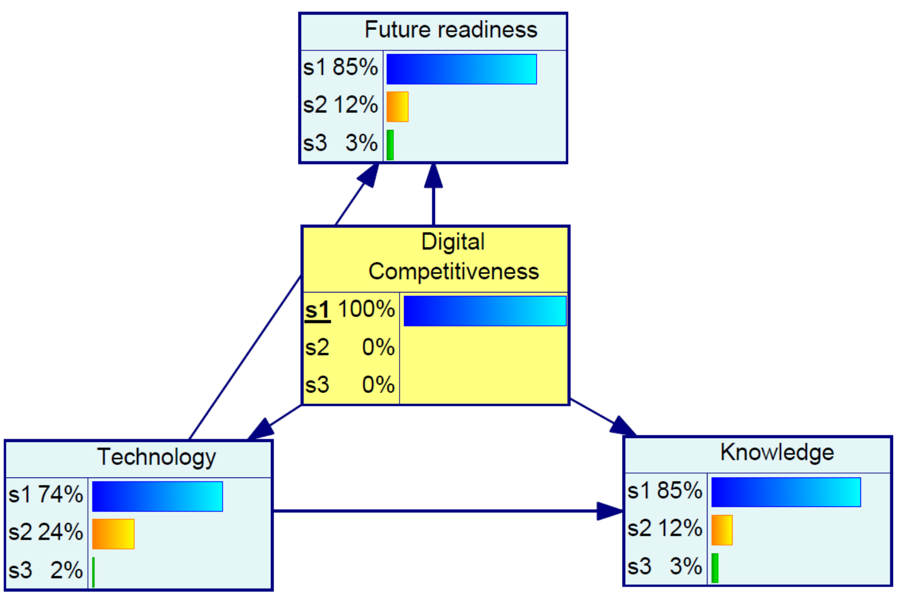
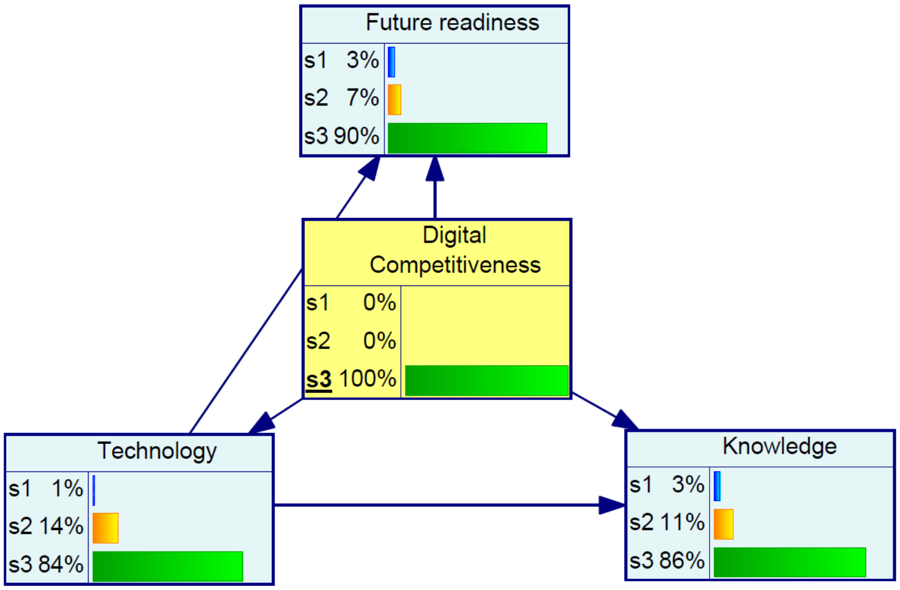


Fig. 1. A BBN model linking digital competitiveness to three pillars (developed in GeNIe software).

Countries exhibiting varying levels of digital competitiveness were evaluated based on their performance across the three pillars, as depicted in Figures 2 (a) and 2 (b). Both illustrations underscore the significance of these pillars in influencing overall digital competitiveness. Countries with high performance demonstrate relatively stronger performance in future readiness and knowledge. Conversely, countries with low performance are notably linked to deficiencies in future readiness.



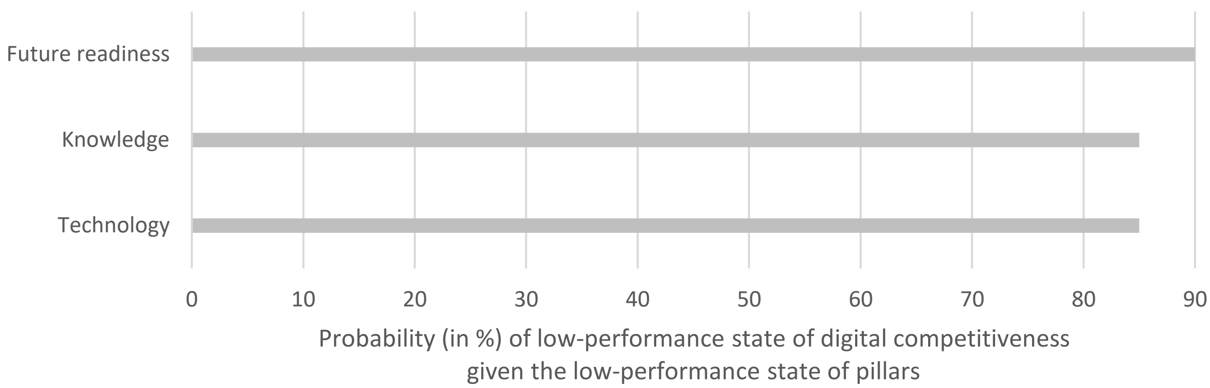
(a)



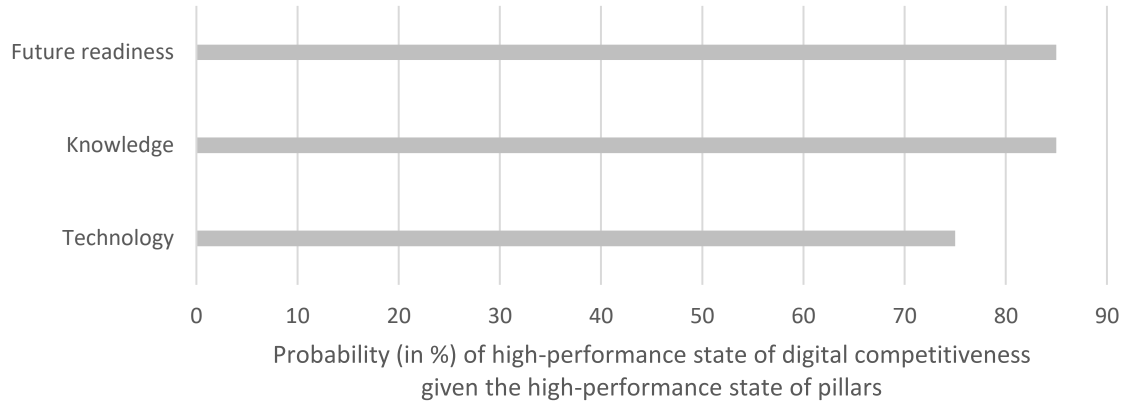
(b)

Fig. 2. A BBN model representing the countries with (a) high; and (b) low performance in digital competitiveness.

The assessment of individual pillars' relative importance was conducted by examining their negative and positive effects on digital competitiveness. Figure 3 (a) demonstrates that low performance (s3) in future readiness significantly impedes digital competitiveness. Conversely, Figure 3 (b) highlights that high performance (s1) in future readiness and knowledge can substantially enhance digital competitiveness.



(a)



(b)

Fig. 3. (a) Vulnerability; and (b) Resilience potential of individual pillars.

The mutual value of information between digital competitiveness and each pillar was assessed using Hugin software (see Figure 4). Unlike the conventional ranking framework that treats the three pillars as equally weighted factors (WDC, 2023), the analysis reveals that future readiness holds the highest informative value, followed by knowledge. Technology emerges as the least informative pillar for predicting digital competitiveness.

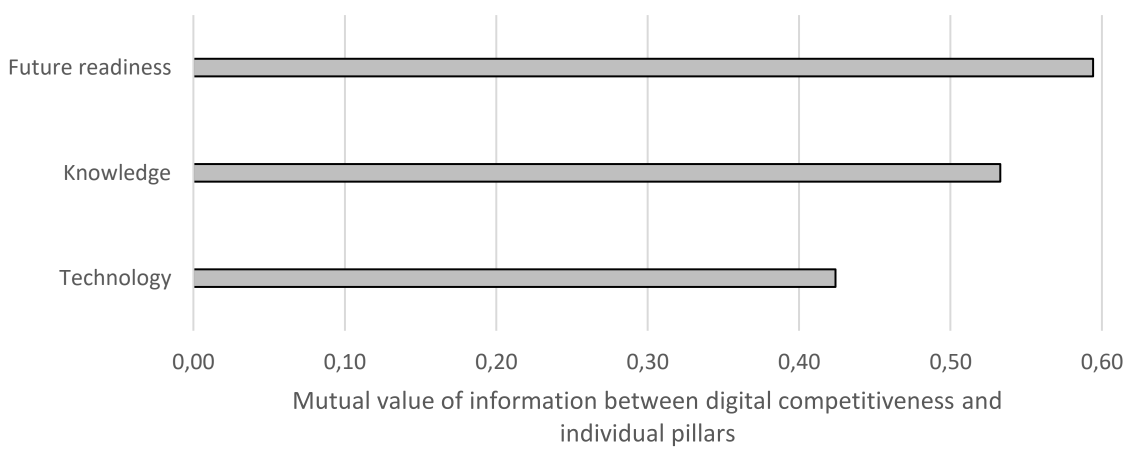


Fig. 4. Mutual value of information.

4.2 BBN model for prioritizing sub-pillars of digital competitiveness

Figure 5 displays the second BBN model, revealing the connectivity of nine sub-pillars to digital competitiveness. Unlike treating these sub-pillars as autonomous factors in the conventional ranking scheme (WDC, 2023), the BBN model reveals interdependencies among them. 'Capital' directly interfaces with 'talent', 'IT integration', and 'regulatory framework'. Similarly, 'scientific concentration' is connected with both 'adaptive attitudes' and 'IT integration'. Furthermore, 'IT integration' is connected with both 'technological framework' and 'training and education,' while 'talent' links to 'business agility'. Each sub-pillar in the model is also denoted by a letter in brackets, representing the corresponding pillar, with K, T, and F symbolizing knowledge, technology, and future readiness, respectively.

Interconnections exist between sub-pillars from different pillars. For example, 'IT integration', 'technological framework', and 'training and education', forming a sub-network, represent different pillars. Moreover, interdependencies are observed among sub-pillars from the same pillar. For instance, 'capital' and 'regulatory framework', both representing technology, are interconnected. 'IT integration' and 'business agility' are indirectly linked through 'capital' and 'talent'.

Each variable follows a uniform distribution due to the utilization of a uniform-width discretization scheme in model development. This implies that countries considered in this study are evenly distributed across the three performance states of each variable.

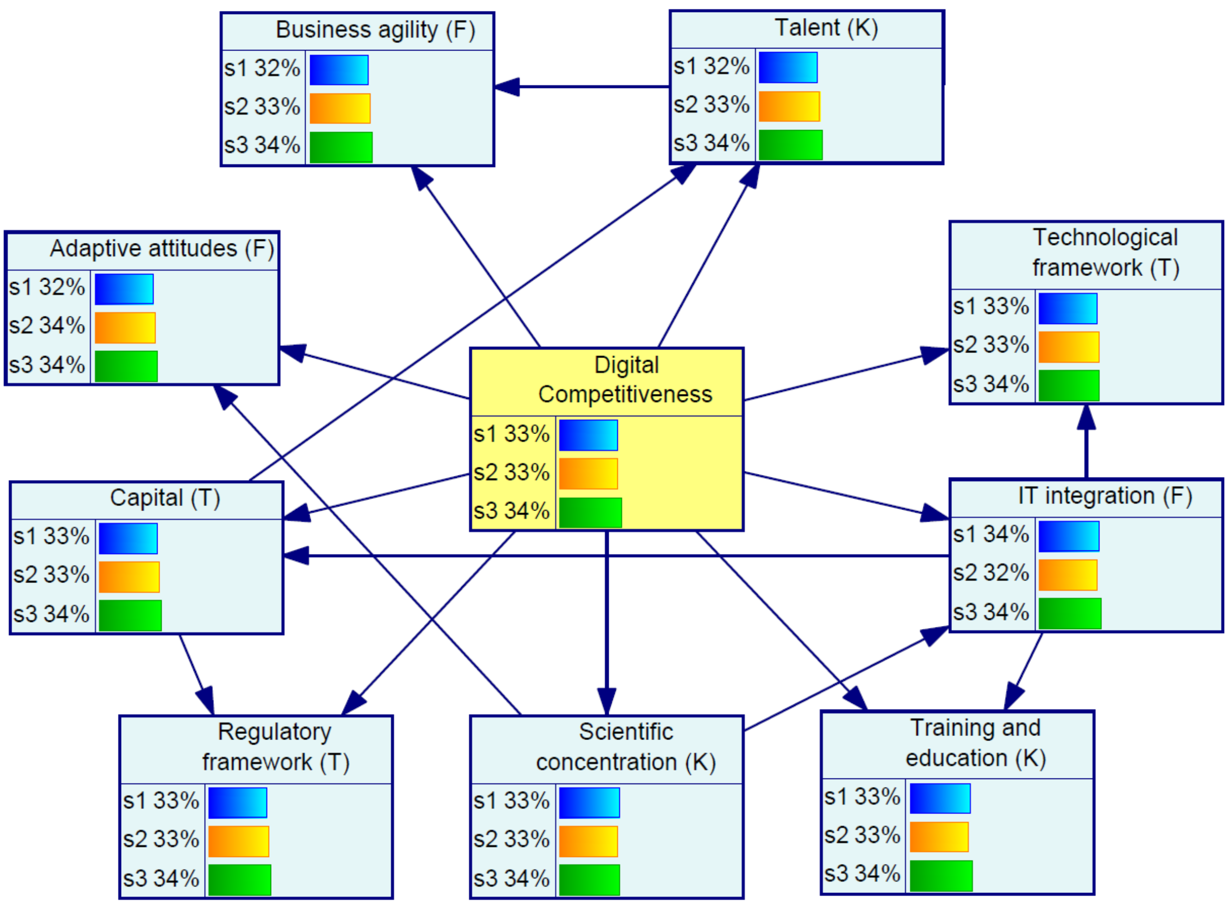
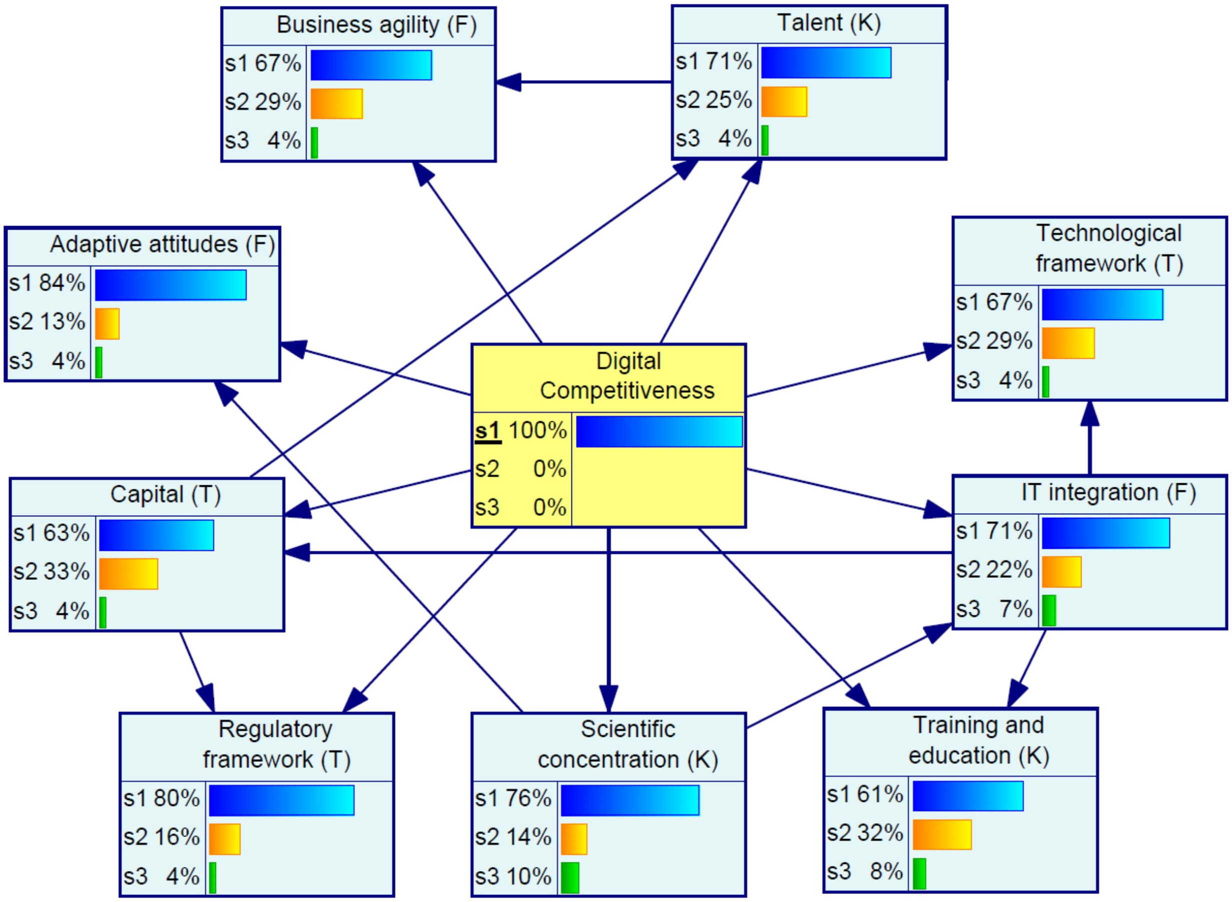


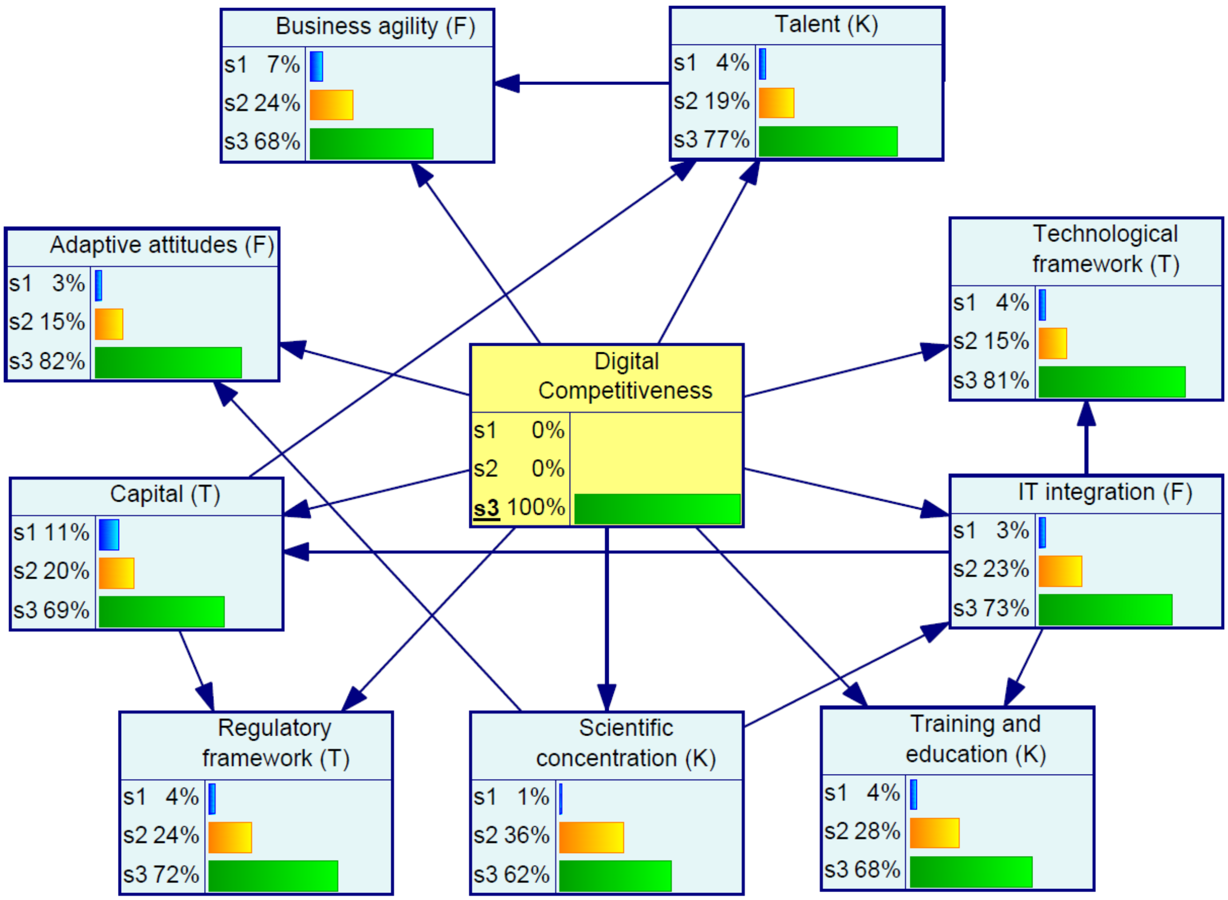
Fig. 5. A BBN model linking digital competitiveness to its sub-pillars.

Countries demonstrating varied levels of digital competitiveness were evaluated for their performance across the nine sub-pillars, as depicted in Figures 6 (a) and 6 (b). Both illustrations underscore the significance of these sub-pillars in influencing overall digital competitiveness.

Countries with high performance exhibit relatively stronger performance in 'adaptive attitudes' and 'regulatory framework'. Conversely, low-performing countries are notably associated with deficiencies in 'adaptive attitudes' and 'technological framework'.



(a)



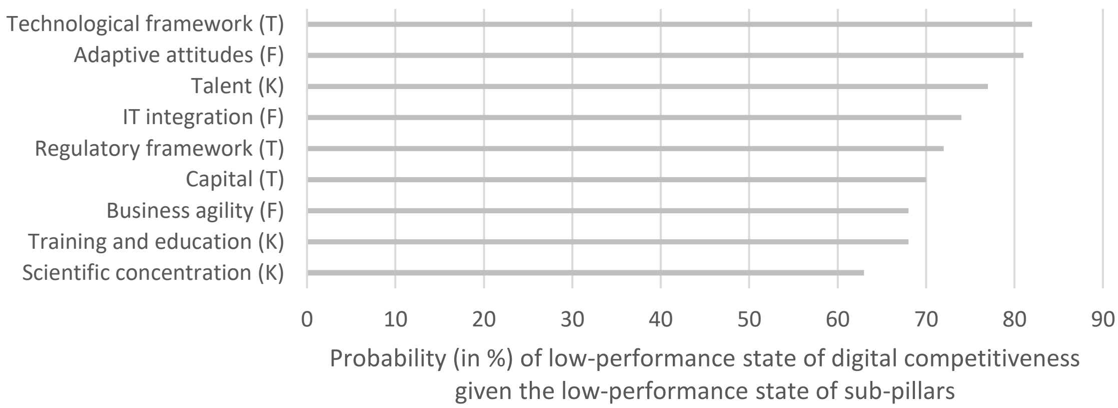
(b)

Fig. 6. A BBN model representing the countries with (a) high; and (b) low performance in digital competitiveness.

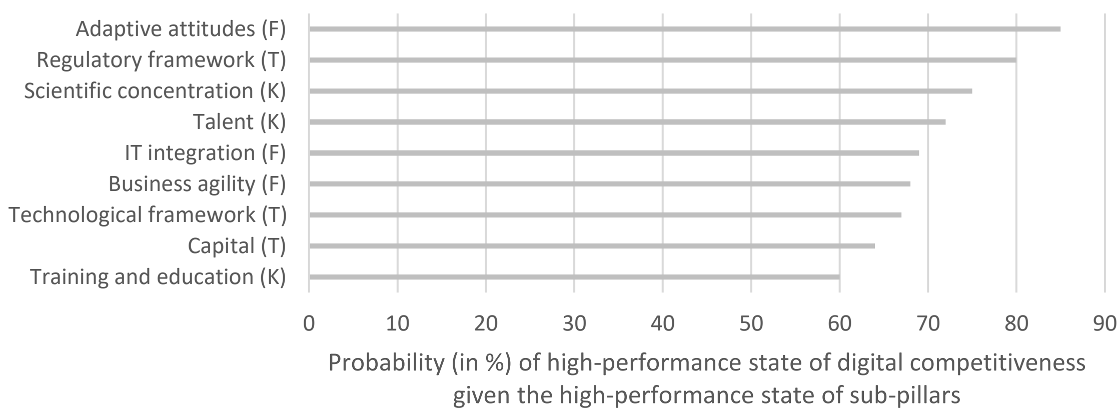
The relative importance of individual sub-pillars was assessed based on their positive and negative impacts on digital competitiveness. Figure 7 (a) illustrates that low performance (s3) in 'technological framework' and 'adaptive attitudes' significantly diminishes digital competitiveness. Conversely, Figure 7 (b) demonstrates that high performance (s1) in 'adaptive attitudes' and 'regulatory framework' can notably enhance digital competitiveness. 'Training and education' appear to be relatively less critical in this context.

This analysis also indicates that sub-pillar prioritization is contingent upon the level of digital competitiveness. Countries striving to improve their digital competitiveness should concentrate on sub-pillars that make a significant positive contribution to competitiveness. Conversely, countries already attaining a high level of competitiveness should focus on crucial sub-pillars with the potential to degrade competitiveness. Remarkably, sub-pillars from all three pillars are well-represented in the list of most critical indicators based on their positive or negative potential.

There are noteworthy disparities between the two ranking schemes. For instance, ‘scientific concentration’ ranks as the least critical sub-pillar based on its negative impact; however, it holds the third position based on its positive impact on digital competitiveness.



(a)



(b)

Fig. 7. (a) Vulnerability and (b) Resilience potential of individual sub-pillars.

The mutual value of information between digital competitiveness and each sub-pillar was evaluated using Hugin software (see Figure 8). Unlike the conventional ranking framework that treats the nine sub-pillars as equally weighted factors (WDC, 2023), the analysis unveils that ‘adaptive attitudes’ emerge as the most informative sub-pillar. Conversely, ‘training and education’ appear to be the least informative sub-pillar for predicting digital competitiveness. Technology-related sub-pillars such as ‘regulatory framework’ and ‘technological framework’ stand out as relatively critical indicators.

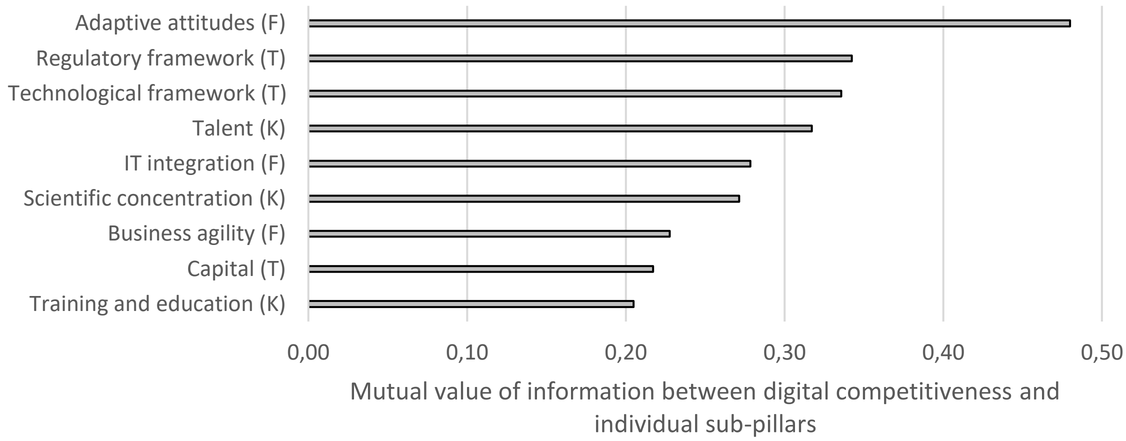
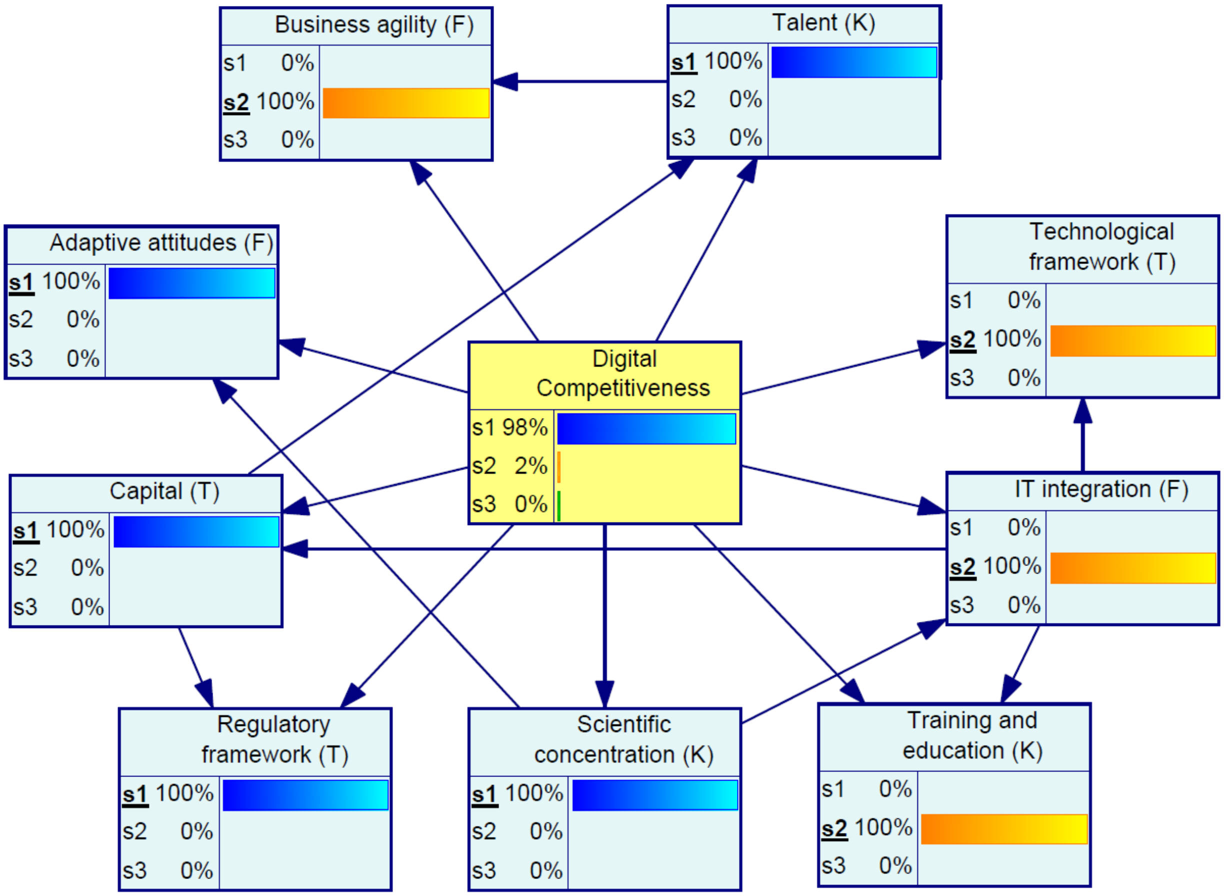


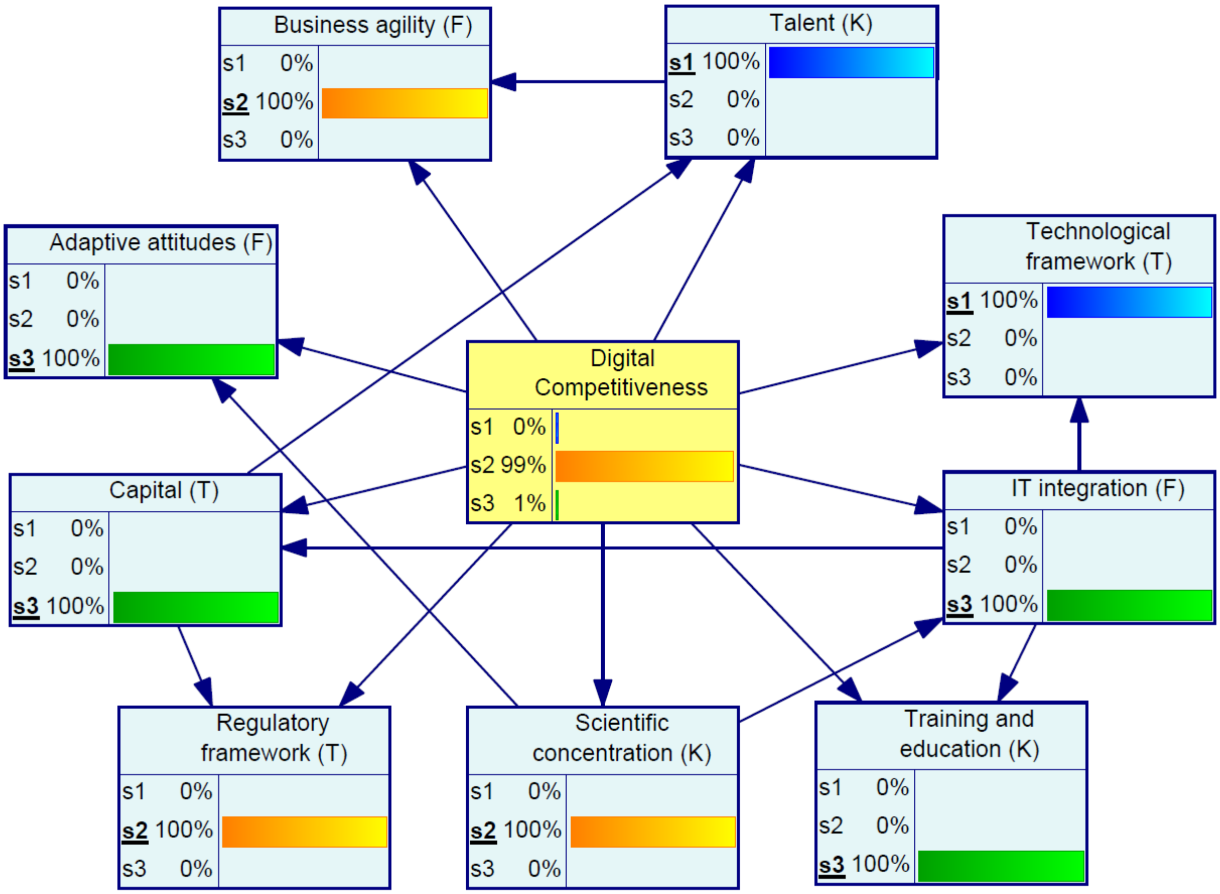
Fig. 8. Mutual value of information.

4.3 Validation of BBN models using case countries

The conventional approach to ranking competitiveness indicators treats them as independent entities (WDC, 2023). However, this study adopts a different approach by assessing countries based on the collective contribution of interdependent indicators towards overall competitiveness. Thus, it is crucial to ascertain whether this approach prioritizes interdependent indicators while maintaining the global ranking of individual countries intact. To explore this, three countries—Australia, Bahrain, and Hungary—were selected, each representing distinct performance levels across the three performance clusters analyzed in the BBN models developed in this study. The BBN models for these countries are depicted in Figures 9 (a), (b), and (c). Each country exhibits a unique combination of performance states across the nine sub-pillars. For instance, Australia is linked with a high-performance state (s1) across the 'talent', 'adaptive attitudes', 'capital', 'regulatory framework', and 'scientific concentration' sub-pillars. Conversely, Hungary displays medium (s2) to low (s3) performance across the nine sub-pillars. The BBN models demonstrate accuracy rates of 98%, 99%, and 97% in predicting the actual digital competitiveness state for Australia, Bahrain, and Hungary, respectively.


Business agility (F)
s1 0%
s2 100%
s3 0%
Talent (K)
s1 100%
s2 0%
s3 0%
Adaptive attitudes (F)
s1 100%
s2 0%
s3 0%
Technological framework (T)
s1 0%
s2 100%
s3 0%
Digital Competitiveness
s1 98%
s2 2%
s3 0%
Capital (T)
s1 100%
s2 0%
s3 0%
IT integration (F)
s1 0%
s2 100%
s3 0%
Regulatory framework (T)
s1 100%
s2 0%
s3 0%
Scientific concentration (K)
s1 100%
s2 0%
s3 0%
Training and education (K)
s1 0%
s2 100%
s3 0%

(a)


Business agility (F)
s1 0%
s2 100%
s3 0%
Talent (K)
s1 100%
s2 0%
s3 0%
Adaptive attitudes (F)
s1 0%
s2 0%
s3 100%
Technological framework (T)
s1 100%
s2 0%
s3 0%
Digital Competitiveness
s1 0%
s2 99%
s3 1%
Capital (T)
s1 0%
s2 0%
s3 100%
IT integration (F)
s1 0%
s2 0%
s3 100%
Regulatory framework (T)
s1 0%
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s3 0%
Scientific concentration (K)
s1 0%
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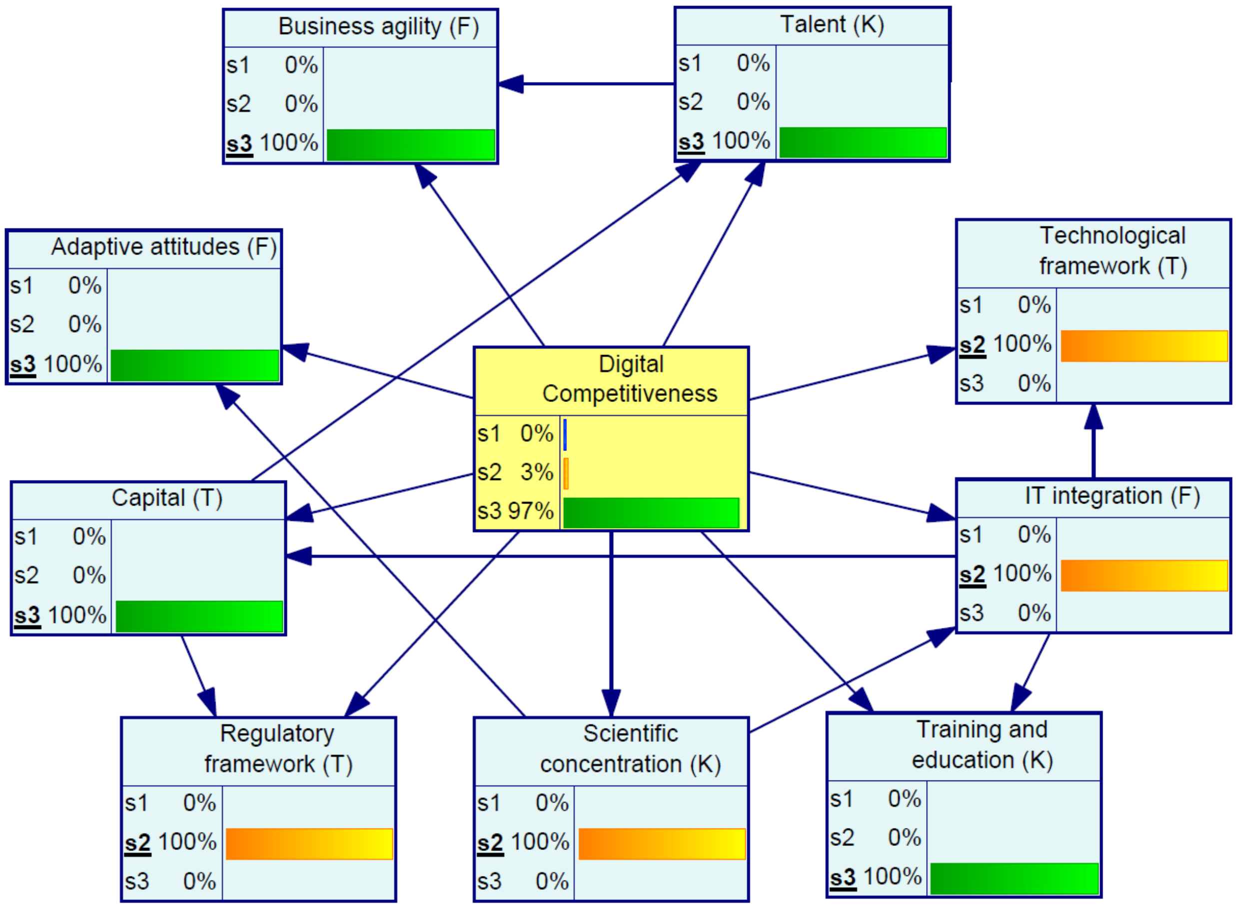
Training and education (K)
s1 0%
s2 0%
s3 100%

(b)



(c)

Fig. 9. A BBN model representing the digital competitiveness of (a) Australia; (b) Bahrain; and (c) Hungary.

5. DISCUSSIONS AND IMPLICATIONS

The BBN models revealed non-linear connections not only among the core pillars but also among their respective sub-pillars. This finding emphasizes the complex and interdependent nature of digital competitiveness. For instance, the direct influence observed between technology and both future readiness and knowledge underscores the pivotal role of technological advancements in driving overall digital capabilities. Moreover, the interconnections among sub-pillars within and across different pillars suggest that improvements in one area can have ripple effects across the entire digital ecosystem, highlighting the need for a holistic approach to digital transformation.

The analysis of country performance across the pillars and sub-pillars revealed disparities in digital competitiveness levels. High-performing countries demonstrated strengths not only in overarching pillars like future readiness and knowledge but also in specific sub-pillars within those pillars. Conversely, low-performing countries exhibited deficiencies in critical areas, indicating the need for targeted interventions and policy reforms. This finding aligns with prior research emphasizing the importance of investments in education, innovation, and digital infrastructure for enhancing digital capabilities (Gruber, 2019). It also underscores the need for tailored strategies to address specific weaknesses and capitalize on strengths in different countries.

The BBN models provided insights into the relative importance of both overarching pillars and specific sub-pillars in shaping digital competitiveness. Future readiness emerged as a critical determinant, with its low performance significantly impeding overall competitiveness. This underscores the importance of fostering digital literacy, promoting innovation, and building resilient digital infrastructure to adapt to rapid technological changes (Tim et al., 2021). Similarly, the significance of knowledge suggests the pivotal role of human capital and knowledge creation in driving digital transformation and competitiveness (Popa et al., 2022). The BBN models also highlighted the criticality of specific sub-pillars, such as adaptive attitudes and regulatory frameworks, in shaping digital competitiveness, underscoring the need for supportive regulatory environments and organizational agility (Tallon et al., 2019).

The evaluation of the mutual value of information between each pillar and digital competitiveness provided additional insights into their relative importance. Future readiness and knowledge emerged as the most informative pillars, emphasizing the need for policies and initiatives aimed at nurturing a skilled workforce, fostering innovation ecosystems, and creating an enabling environment for digital transformation. Additionally, technology-related sub-pillars, such as regulatory frameworks and technological infrastructure, were found to be critical indicators, highlighting their role in shaping a country's digital competitiveness.

The findings from this study align with and extend existing literature on digital competitiveness. While some findings confirm prior research, such as the importance of education and regulatory frameworks (Benvenuti et al., 2023), others offer novel insights, such as the intricate interdependencies among sub-pillars across different pillars. This unique analysis enriches theunderstanding of digital competitiveness dynamics and highlights the need for holistic approaches in policymaking and strategic planning.

The findings of this study carry significant theoretical and managerial implications for understanding and enhancing digital competitiveness. By employing BBN models, the approach reveals the complex interdependencies among pillars and sub-pillars, offering insights distinct from traditional, linear models.

The results underscore that while the conventional approach may yield similar overall rankings, it fails to capture the nuanced importance of individual pillars and sub-pillars. Unlike the conventional method, which treats all pillars as equally important and assigns equal weights to sub-pillars (WDC, 2023), the approach prioritizes factors based on their actual impact on digital competitiveness. This enables policymakers to allocate resources more effectively, focusing on areas that offer the highest potential for improving competitiveness.

Furthermore, the ability of this approach to differentiate between the relative importance of factors allows policymakers to tailor strategies to the unique circumstances of their countries. For instance, countries with high performance in certain pillars may prioritize maintaining or further enhancing those strengths, while simultaneously addressing weaknesses in other areas. Conversely, countries with low performance may focus on targeted interventions to improve critical sub-pillars, thereby bolstering overall competitiveness.

Additionally, the findings offer insights into resource allocation, enabling policymakers to allocate resources more efficiently. By investing in areas with the highest impact on digital competitiveness, countries can maximize the effectiveness of their investments and accelerate their digital transformation efforts. For example, directing resources towards improving future readiness and knowledge may yield significant dividends in terms of enhancing overall competitiveness.

Moreover, the approach facilitates evidence-based policymaking by providing policymakers with data-driven insights into the factors driving digital competitiveness. By leveraging the relative importance of pillars and sub-pillars, policymakers can develop targeted interventions and policies that address specific challenges and capitalize on opportunities for enhancing digital capabilities.

6. CONCLUSIONS

The main objective of this study was to explore the complex dynamics of digital competitiveness by examining the interdependencies among pillars and sub-pillars using BBN models. This study aimed to provide a better understanding of digital competitiveness that goes beyond traditional linear approaches and highlights the differential importance of individual factors.

Through the analysis of BBN models, the objective was achieved by uncovering connections among pillars and sub-pillars, revealing how these factors collectively shape digital competitiveness. The findings offer insights into the relative importance of different pillars and sub-pillars, providing policymakers with valuable information for prioritizing resources and developing targeted interventions to enhance digital capabilities.

Key findings from thisstudy include the critical role of future readiness and knowledge in driving digital competitiveness, the differential impact of factors across countries, and the importance of adopting a holistic approach that considers the interconnectedness of various factors. Furthermore, the approach highlights the limitations of traditional ranking schemes that treat all pillars and sub-pillars equally, emphasizing the need for robust methodologies that capture the complex dynamics of digital competitiveness.

This study has certain limitations. The analysis relies on data from a specific year and may not capture longitudinal changes in digital competitiveness. The analysis was confined to a relatively limited number of countries, encompassing a dataset of 64 countries. While this dataset provided valuable insights into the dynamics of digital competitiveness, a broader sample including a more extensive range of countries could offer a more comprehensive understanding of global trends and variations. Future research should aim to expand the scope of analysis to encompass a more diverse array of countries, allowing for a detailed examination of regional disparities and contextual factors influencing digital competitiveness.

Additionally, this study used a discretization scheme that categorized variables into three states, which may oversimplify the complexities of digital competitiveness. Future research could explore alternative discretization methods or incorporate continuous variables to provide a more granular analysis of the factors influencing digital competitiveness. Moreover, the use of the TAN algorithm, while valuable for its interpretability, may have limitations in capturing complex relationships among variables. Future studies could explore alternative machine learning techniques or hybrid models to overcome these limitations and enhance the accuracy of predictions.

Future research could explore longitudinal changes in digital competitiveness to provide insights into evolving trends and dynamics. Additionally, further refinement of BBN models and incorporation of additional data sources could enhance the accuracy and reliability of predictions. Moreover, comparative studies across different regions and industries could provide valuable insights into the factors driving digital competitiveness in diverse contexts.

Appendix

Table A1. World Digital Competitiveness Ranking of Countries (source: WDC (2023))

Country	Overall	Knowledge	Talent	Training and education	Scientific concentration	Technology	Regulatory framework	Capital	Technological framework	Future readiness	Adaptive attitudes	Business agility	IT integration
Argentina	61	62	61	60	50	63	57	63	56	49	55	38	53
Australia	16	15	8	28	16	18	15	16	31	20	4	42	23
Austria	22	16	20	11	17	35	34	34	38	19	24	22	13
Bahrain	38	36	15	55	34	30	29	47	14	46	49	32	50
Belgium	15	12	7	22	18	19	5	18	39	16	39	9	15
Botswana	60	52	37	41	64	52	54	6	63	63	63	46	63
Brazil	57	57	64	57	25	60	58	62	51	52	51	61	45
Bulgaria	55	53	58	46	44	56	60	54	50	58	50	62	57
Canada	11	4	9	2	5	13	19	4	26	11	18	24	4
Chile	42	47	41	45	56	38	37	50	30	38	25	52	34
China	19	21	14	43	9	22	20	26	20	13	20	4	32
Colombia	62	54	57	42	57	62	62	57	62	60	58	59	58
Croatia	44	40	54	36	32	42	47	33	44	50	41	57	48
Cyprus	51	48	55	44	40	53	53	56	49	53	46	63	39
Czech Republic	24	24	17	33	27	26	33	13	28	27	34	12	30
Denmark	4	9	5	12	20	7	10	10	6	3	8	6	2
Estonia	18	25	28	8	43	23	18	35	13	9	9	23	5
Finland	8	11	11	19	13	9	3	7	11	5	3	21	3
France	27	22	24	29	14	20	21	28	19	35	43	41	24
Germany	23	14	26	14	7	34	32	21	47	24	28	20	18
Greece	52	51	53	59	31	47	46	37	52	57	61	60	43

Country	Overall	Knowledge	Talent	Training and education	Scientific concentration	Technology	Regulatory framework	Capital	Technological framework	Future readiness	Adaptive attitudes	Business agility	IT integration
Hong Kong SAR	10	6	6	5	8	2	6	14	1	17	5	16	47
Hungary	47	46	45	47	42	36	35	46	29	61	62	55	37
Iceland	17	32	32	26	37	8	11	27	4	14	11	13	31
India	49	45	34	48	52	50	52	23	60	51	60	30	52
Indonesia	45	60	42	61	59	39	45	3	57	43	54	10	59
Ireland	21	19	16	24	24	28	9	42	35	22	19	15	35
Israel	13	8	23	3	3	24	25	25	23	12	30	19	1
Italy	43	43	46	58	23	46	41	48	45	37	31	33	41
Japan	32	28	49	21	15	32	50	36	7	32	22	56	16
Jordan	50	59	38	50	63	48	42	44	54	45	53	29	46
Kazakhstan	34	30	47	1	49	41	22	53	48	31	29	5	54
Korea Republic	6	10	31	6	2	12	26	24	8	1	1	3	12
Kuwait	41	44	43	53	35	37	44	40	25	41	36	47	40
Latvia	40	39	44	31	54	43	43	52	27	34	35	49	21
Lithuania	28	23	25	15	33	33	28	39	33	28	37	18	28
Luxembourg	26	33	40	18	48	25	17	29	34	21	23	27	10
Malaysia	33	29	30	17	36	27	36	32	16	33	27	37	33
Mexico	54	50	52	54	46	58	59	55	55	54	56	53	51
Mongolia	63	56	63	37	61	61	61	61	58	62	44	64	62
Netherlands	2	7	3	23	12	5	2	2	10	4	6	8	7
New Zealand	25	34	33	32	30	21	24	19	24	25	12	40	22
Norway	14	20	21	16	22	14	13	20	21	15	15	26	17
Peru	56	55	59	38	62	57	51	51	59	55	47	48	61
Philippines	59	63	56	62	58	51	63	41	43	59	59	50	60
Poland	39	37	36	39	28	44	49	43	37	40	45	28	44

Country	Overall	Knowledge	Talent	Training and education	Scientific concentration	Technology	Regulatory framework	Capital	Technological framework	Future readiness	Adaptive attitudes	Business agility	IT integration
Portugal	36	31	29	34	26	40	27	49	46	36	26	58	25
Qatar	29	38	10	51	60	16	23	22	18	26	33	11	27
Romania	48	49	50	56	47	49	39	59	40	47	48	45	42
Saudi Arabia	30	35	19	30	55	17	14	9	36	30	32	25	29
Singapore	3	3	4	9	11	1	1	15	2	10	13	14	11
Slovak Republic	46	42	48	40	39	54	55	58	42	48	52	51	36
Slovenia	37	27	39	13	29	45	48	38	41	39	38	39	38
South Africa	58	58	60	49	53	59	56	45	61	56	57	54	56
Spain	31	26	27	35	19	31	38	30	22	29	21	43	19
Sweden	7	5	13	4	4	11	7	8	17	8	10	17	8
Switzerland	5	1	2	7	10	10	4	11	12	6	16	7	6
Taiwan	9	18	22	10	21	3	16	5	5	7	17	1	14
Thailand	35	41	35	52	38	15	31	12	15	42	42	34	49
Turkey	53	61	51	63	41	55	40	60	53	44	40	35	55
UAE	12	17	1	25	51	4	8	17	3	23	14	31	26
UK	20	13	18	27	6	29	30	31	32	18	7	36	20
USA	1	2	12	20	1	6	12	1	9	2	2	2	9
Venezuela	64	64	62	64	45	64	64	64	64	64	64	44	64

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